ATMOSPHERIC REMOTE SENSING USING SPACE-BASED RADIO NAVIGATION SATELLITES

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ABSTRACT

Given that agricultural cycles, human well-being, economic growth and many societal activities are affected by climate variability, a greater understanding of critical atmospheric parameters (such as refractivity, pressure, temperature and humidity) is of paramount importance. Recently many countries have investigated the feasibility of using the space-based radio navigation satellites of the Global Positioning System (GPS) for weather and environmental studies. There are two primary methods by which GPS can be used to actively sense relevant atmospheric constituents: the ground-based atmospheric sounding method and GPS radio occultation method. Both techniques are based on using the transmitted GPS satellite radio signals to measure atmospheric profiles of refractivity. As the GPS technology is relatively new to the Malaysian weather forecasting community, this paper describes the principles underpinning both atmospheric sensing techniques. Further discussion includes the presentation of an overview of studies conducted abroad, at various scales ranging from national to global. Although GPS has the potential to improve numerical weather prediction, climate analysis and space weather forecasting, it is noted that significant research is still required in order to assess its true potential for equatorial atmospheric studies. Nevertheless, if appropriate strategies are employed during the data acquisition and data processing phases, GPS is capable of being implemented as an alternative and promising tool to remotely sense the spatial and temporal variability of the Earth's atmosphere.

Keywords: GPS; ground-based atmospheric sounding; radio occultation

INTRODUCTION

Variability of weather conditions is inevitable, continuous and all-pervasive on the Earth's surface. It influences to not only the agricultural cycle and human well-being, but also to many economic and societal activities. Prolonged and destructive droughts over the grain and paddy belts, for example, lead to shortages of food. Heavy precipitation, thunderstorms, floods and hurricanes on the other hand, account for huge losses of farmland and crops, housing and infrastructure. To accurately monitor and predict the state of the weather, with the ultimate aim of minimizing losses of life and property, knowledge of the quantitative state of the atmosphere is of paramount importance. To remotely sense the spatial and temporal variability of the Earth's atmosphere, a variety of atmospheric sensing platforms and techniques have been developed during the past decades. These include routine surface meteorological sensors, radiosondes, radiometers, Radio Detection and Ranging (RADAR), weather aircraft, Light Detection and Ranging (LIDAR) and the use of satellite images; each with its own advantages and limitations.

GPS is an emerging satellite-based radio navigation technology for weather and environmental studies. It is based on the transmitted GPS satellite radio signals that can be used to measure atmospheric profiles of refractivity. GPS is an all-weather satellite-based radio navigation system operated by the United States Department of Defense. GPS consists of a nominal constellation of 32 operational satellites in near-circular orbits of approximately 26,560km radius (12 hr sidereal periods). There are two primary GPS methods for actively sensing atmospheric constituents: the ground-based atmospheric sounding method and the GPS radio occultation (RO) method. As GPS technology is relatively new to the Malaysian weather forecasting community, this paper describes the basic principles of both atmospheric sensing techniques.

GPS METEOROLOGY

Suggestions about the utility of GPS for atmospheric sensing appeared in the literature as early as 1990 [1]. As GPS signals propagate through the atmosphere, they are affected by changes in the refractive indices within the signal path caused by moisture, pressure and temperature. Atmospheric refractive indices in general cause an excess group delay of the GPS signal in relation to free-space propagation. Resolving the delay in terms of atmospheric parameters using data collected by geodetic-quality GPS receivers is the basis for GPS meteorology.

Often considered a nuisance by geodesists and surveyors who are interested only in using GPS for high accuracy relative positioning, refractivity can be divided into dispersive and non-dispersive components. The dispersive component depends on molecular resonances in the vicinity of the propagation carrier frequency. Here, *N* is directly proportional to the electron density. Similarly, since GPS carrier frequencies are far very different from molecular resonances, their influence can be therefore be disregarded. As far as the non-dispersive component is concerned, refractivity can be grouped into hydrostatic and wet components. The hydrostatic component characterizes the effect of the induced dipole moment of the dry constituent. The wet component on the other hand characterizes the dipole moment of water vapour, along with the orientation effects of the permanent dipole moment of water molecules. In general, the total refractivity can be expressed as [2]:

$$N(f) = N_0 + N^{'}(f) + iN^{''}(f) \tag{1}$$

where f is the signal frequency in hertz, N_0 and $N'(f)$ are the non-dispersive and dispersive components of refractivity associated with the real part of the permittivity, and $N''(f)$ is the attenuation which is related to the imaginary part of the permittivity. Based on Eq. (1), the dependency of phase refractivity on atmospheric variables can be expressed as [3]:

$$N = 77.6\frac{P}{T} + 3.73\times 10^5\left(\frac{P_w}{T^2}\right) - 4.03 n_e / f^2 \tag{2}$$

where P is the total atmospheric pressure in mbar, P_w is the partial pressure of water vapours in mbar, T is the temperature in degrees Kelvin, and n_e is the free electron density in electrons per cubic metre. Further discussion on the theory of signal propagation delays induced by dry air, water vapour, hydrometeors and other particulates (e.g. sand, dust, aerosols and volcanic ash) in the atmosphere is given in [2].

As mentioned earlier, there are two main approaches to remotely sense the spatial and temporal variability of the Earth's atmosphere using GPS: ground-based atmospheric sounding and the GPS-RO method. Both techniques in general aim to improve numerical weather prediction (NWP), climate analysis and space weather forecasting. As ground-based atmospheric sounding is capable of sensing the Integrated Water Vapour (IWV) along the GPS signal path, the atmospheric parameters obtained from RO observations extend from the fundamental variables (e.g., temperature, density, pressure, water vapour, trace gases, aerosols and cloud liquid water) to ionospheric electron density. Fig. 1 provides an overview of GPS meteorology.

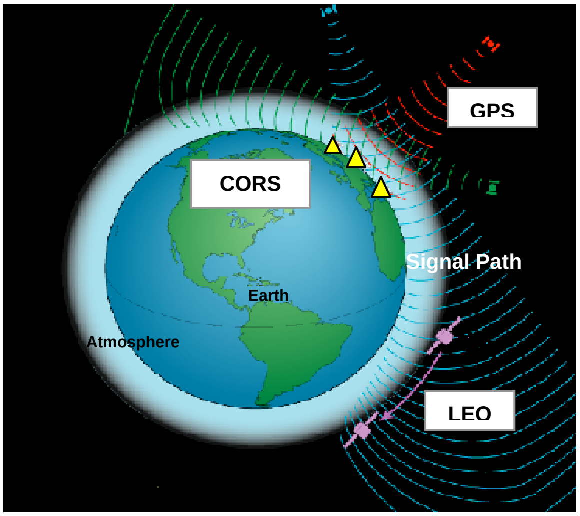

Figure 1: Principles of GPS Meteorology

GPS GROUND-BASED ATMOSPHERIC SOUNDING

Ground-based atmospheric sounding takes advantage of the dual-frequency signals (L1 and L2) collected by a GPS receiver at a fixed point on the ground. By using existing continuously operating reference stations (CORS), the observations made on these signals can then be assimilated to quantify the water vapour along the path from the GPS satellites to the receiver (see Fig. 2). Water vapour is a greenhouse gas that plays a decisive role in the balance of planetary radiation. This role is not restricted to absorbing and radiating energy through evaporation and condensation processes, but includes the effect it has on the formation of clouds and aerosols and the chemistry of the lower atmosphere. Most of the water vapour in the atmosphere resides in the troposphere, which ranges in height up to about 9km at the poles and more than 16km at the equator. Being one of the most significant yet poorly understood atmospheric constituents, improving the ability to monitor water vapour will lead to more accurate forecasts of extreme weather events and a better understanding of environmental processes.

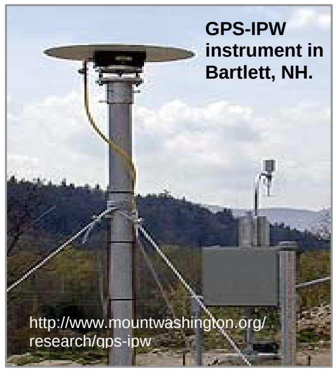

Figure 2: Typical GPS-IWV CORS

Dual-frequency GPS measurements over a CORS network can be processed to extract the slant IWV values along the signal paths from the GPS satellites to the ground receivers, or alternatively the vertical IWV over the CORS stations, with an accuracy of about 1mm [4]. IWV retrieval error budget can be kept to below 0.5mm if the GPS measurements are integrated with surface pressure measurements with accuracy of about 0.5hPa and surface temperature measurements with an accuracy of about 2˚ [5]. Using a CORS network of reasonable size and varying receiver heights, the three-dimensional structure of the inhomogeneous atmospheric water vapour can be estimated using the tomographic technique [6][7]. The accuracy of water vapour retrievals however, depends on two factors: the accuracy of the measurements needed to estimate the total refractivity of the neutral atmosphere from the GPS observables and the accuracy of the assumptions and/or mathematical models underpinning these analyses [8].

CORS networks can provide unattended, continuous, independent, frequent, and accurate observations of IWV at very low cost. There have been extensive experiments conducted at various scales ranging from national to global. In general, many of these studies have assessed the accuracy of IWV estimation and investigated the degree of improvement in near-real-time weather prediction. Other studies have focused on the development and refinement of the observation techniques, data processing and assimilation of the GPS results into NWP. Examples of ground-based atmospheric sounding projects include the GPS Earth Observing Network (GEONET), the National Oceanic and Atmospheric Administration (NOAA) GPS-Met Project, and the GPS Atmosphere Sounding Project (GASP).

GPS Earth Observing Network (GEONET). GEONET is a GPS CORS network operated by the Geographical Survey Institute (GSI) of Japan since 1994. Equipped with high accuracy dual-frequency receivers, it was principally developed for crustal motion and deformation studies. Currently, there are about 1224 GEONET stations with a mean separation of 17km. As far as GPS meteorology is concerned, ground-based atmospheric sounding in Japan has been developed along with GEONET. Although GEONET stations do not have in-situ pressure and temperature observations, the GPS-IWV retrieval for assimilation into NWP has been found to be of high accuracy and in reasonable agreement with radiosonde data [9].

NOAA GPS-Met Project. For the NOAA GPS-Met Project, a network of about 500 CORS sites across the U.S., Canada, Mexico and the Caribbean has been used [10]. The purpose of this project is to evaluate the engineering and scientific bases for ground-based atmospheric sensing. Moreover, the aim was also to demonstrate the feasibility of using ground-based atmospheric sensing for improved weather forecasting, climate monitoring and satellite sensor calibration/validation; and to transform the observing system technology into operational use. Unlike Japan's GEONET, the NOAA GPS-Met network not only consists of geodetic-grade GPS receivers but also integrated surface meteorological sensors. The network design and results are discussed in [11].

GPS Atmosphere Sounding Project (GASP). The GASP project consists of data generation, transmission and analysis components. Moderated by the GeoForschungsZentrum (GFZ), it was financed by the Helmholtz Association of German Research Center. Began in 2000, currently there over 200 sites mostly from the Satellite Positioning Service (SAPOS) of the German National Survey, with an average separation of about 50km. GASP aims to develop a system for the operational determination of IWV and to assimilate these data into NWP models. For some stations, surface meteorological data are also available. However, for most of the sites the required pressure and temperature data have to be interpolated using the synoptic sites of the German Weather Service (about 200 sites) with an accuracy ranging from 0.3hPa to 1.0hPa [12]. However, in spite of concentrating on ground-based atmospheric sensing, GASP also supports RO projects such as the Challenging Minisatellite Payload (CHAMP).

GPS RADIO OCCULTATION

Unlike GPS ground-based atmospheric sounding, space-borne RO exploits the GPS signals bending and being delayed by atmospheric refraction, as observed from Low Earth Orbiting (LEO) satellites. With a GPS receiver on board a LEO satellite (see Fig. 3), setting or rising radio occultation events (ROEs) are observed by the RO antenna(s) as the transmitted GPS signals pass through the Earth's atmosphere. The signal phase and amplitude variations are recorded by the space-borne receiver. The excess phase delays of the signals introduced by the Earth's atmosphere is extracted from the phase measurements after the precise orbit of the LEO satellite and the clock errors of both the LEO and GPS satellites are determined. The bending angle profiles over the RO points are then derived from the excess phase, amplitude, and positions and velocities of LEO and GPS satellites, from which corresponding refractivity profiles are inverted and water vapour profiles are retrieved using auxiliary atmospheric information (from other independent methods such as NWP models and radiosonde observations).

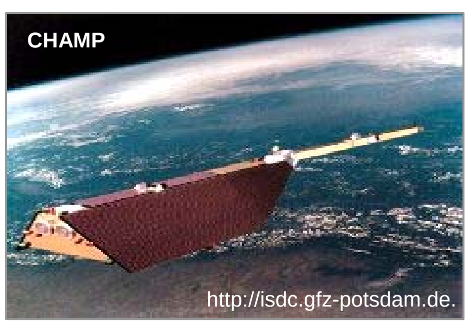

Figure 3: Example of LEO Satellite

Both bending angles and refractivity profiles are retrieved from the excess phase and amplitude observations. The inverse problem, i.e. construction of the electromagnetic field from the refractivity profile (or the bending angle) and the path of the receiving and transmitting antennas, are solved using the principles of geometrical optics [13]. Either bending angle or refractivity can be directly used as observation operators in the data assimilation process. Recent research suggests inversion methods other than those based on classical geometric optical could improve this process [14].

The quality of GPS-RO sounding is independent of geographical location. It utilizes the highly coherent radio signals that have many unique characteristics, including high accuracy, high vertical resolution, all-weather sounding capability, independent of radiosonde or other calibration, no instrument drift and no satellite-to-satellite bias [14]. Examples of possible applications of GPS-RO data to meteorology and climate have been described in [15]. Launched at Vandenberg Air Force Base, California, in 1995, GPS/MET was the first occultation proof-of-concept experiment. Following the success of the GPS/MET experiment, several other RO missions have been launched. These include the German-U.S. Challenging Minisatellite Payload (CHAMP), the Argentinean Satelite de Aplicaciones Cientificas-C (SAC-C), the U.S.-Europian Gravity Recovery and Climate Experiment (GRACE), the U.S.-Taiwan Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC), the Equatorial Atmosphere Research Satellite (EQUARS), the European Meteorological Operational satellite (MetOp-A), the German TerraSar-X and the National Polar Orbiting Operational Environmental Satellite System (NPOESS).

Challenging Minisatellite Payload (CHAMP). Launched in July 2000, the CHAMP project resulted in significant progress for the GPS-RO technique. The CHAMP project aimed to also determine the Earth’s gravity and magnetic fields, in addition to atmospheric sounding. Furthermore, CHAMP also focused on accurate monitoring of ocean circulation, global sea level changes and short-term changes in the global water balance [16]. Carrying a Jet Propulsion Laboratory (JPL) state-of-the-art Blackjack GPS receiver, the occulting LEO satellite was launched into an almost circular, near-polar orbit (inclination 87.2˚) with an initial altitude of 454km. CHAMP also consisted of ground infrastructure: Raw Data Center, fiducial GPS ground network (GASP), Precise Orbit Determination facility and Occultation Processing System [17]. The CHAMP occultation data and the results of the operational data analyses can be retrieved via the CHAMP Information System and Data Center (ISDC) at http://isdc.gfz-potsdam.de.

Gravity Recovery and Climate Experiment (GRACE). The U.S.-German GRACE project is the first mission in NASA’s Earth System Science Pathfinder series. GRACE aims to map the global gravity field with unprecedented accuracy, with the integration of the GRACE-derived time-varying gravity information and altimetry data over oceans contributing significantly to our understanding of anthropogenic climate change [18]. Similar to CHAMP, GRACE has a JPL Blackjack GPS receiver embedded in the carbon fibre reinforced plastic body panels’ twin satellites [19]. Both GRACE occulting satellites are in an almost circular, near-polar orbit (inclination 89˚) with an initial altitude of 500km and a 200km along-track separation.

Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC). The COSMIC project aims to measure pressure, temperature, humidity, refractivity and ionospheric parameters using data from a constellation of six microsatellites equipped with GPS receivers launched in 2005. Operated by the Satellite Operations Control Center (SOCC) at the National Space Organization (NSPO) in Hsin-Chu, Taiwan, these microsatellites enable GPS-RO observations to be made. Furthermore, a global ground fiducial network based on existing NASA and international CORS networks has been established to support the mission. The COSMIC

Data Analysis and Archive Center (CDAAC) was established in order to process not only COSMIC RO data but also SAC-C and CHAMP data. To support its use in operational NWP, the COSMIC data are available in near real-time (within 2 hours of observation). For the purpose of climate research applications, high quality COSMIC data are available with about two weeks latency.

CONCLUDING REMARKS

The environment is the sum of many factors including weather phenomena and climatic influences. An examination of factors influencing the supplies of food and water, life cycle, human well-being, economic growth and societal activities brings into immediate focus the crucial role played by weather and climate. Accurate predictions on the state of the weather are useful in planning a great variety of human endeavours. Based on a series of comprehensive studies carried out abroad, GPS represents a significant improvement in weather and environmental sensing using space-based radio navigation satellite technology. Because of its long-term practicality, accuracy and data continuity, this GPS-based atmospheric sensing technique is effective in overcoming the shortcomings of other commonly-used atmospheric sounding methods. Although GPS has the potential to augment NWP, climate analysis and space weather forecasting, significant research is still required to assess its full potential, and to understand the observational error characteristics and to develop appropriate data processing procedures. GPS is potentially capable of being implemented as an alternative and promising tool to remotely sense the spatial and temporal variability of the Earth's atmosphere.

REFERENCE

[1] T.H. Dixon and S.K. Wolf, "Some Tests of Wet Tropospheric Calibration for the Casa Uno Global Positioning System experiment," *Geophysical. Research. Letter*, vol. 17, pp. 203-206, 1990.

[2] F.S. Solheim, J. Vivekanandan, R.H. Ware and C. Rocken, "Propagation Delays Induced in GPS Signals by Dry Air, Water Vapor, Hydrometeors and Other Particulates," *Journal of Geophysical Research*, vol. 104, pp. 9663-9670, 1999.

[3] F.R. Kursinski, G.A. Hajj, S.S. Leroy and B. Herman, "The GPS Radio Occultation Technique," *Terrestrial, Atmospheric and Oceanic Sciences*, vol. 11, pp. 53-114, 2000.

[4] M. Bevis, S. Businger, T. Herring, C. Rocken, R. Anthes and R.H. Ware, "GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System," *Journal of Geophysical Research*, vol. 97, pp. 15787-15801, 1992.

[5] S.I. Gutman, S.R. Sahm, S.G. Benjamin and T.L. Smith, "A New Composite Observing System Strategy for GPS Meteorology," in *12th Symposium on Meteorological Observations and Instrumentation*, AMS, Long Beach, CA, 2003.

[6] C. Champollion, F. Masson, M.-N. Bouin, A. Walpersdorf, E. Doerflinger, O. Bock and J.V. Baelen, "GPS Water Vapor Tomography: Preliminary Results from the ESCOMPTE Field Experiment," *Atmospheric Research*, vol. 74, pp. 253–274, 2005.

[7] T. Nilsson and L. Gradinarsky, "Water Vapor Tomography Using GPS Phase Observations: Simulation Results," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, pp. 2927-2941, 2006.

[8] S.I. Gutman, S.R. Sahm, S.G. Benjamin and T.L. Smith, "GPS Water Vapor Observation Errors," in *8th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, Seattle, WA, 2004.

[9] T. Iwabuchi, I. Naito and N. Mannoji, "A Comparison of Global Positioning System Retrieved Precipitable Water Vapor with the Numerical Weather Prediction Data over the Japanese Islands," *Journal of Geophysical Research* vol. 105(4), pp. 4573-4585, 2000.

[10] NOAA, "NOAA/GSD Ground-Based GPS Meteorology (GPS-MET)" (http://gpsmet.noaa.gov/jsp/index.jsp). (last accessed 01/09/08)

[11] D. E. Wolfe and S. I. Gutman, "Developing an Operational, Surface-Based, GPS, Water Vapor Observing System for NOAA: Network Design and Results," *Journal of Atmospheric and Oceanic Technology*, vol. 17, pp. 426-4.40, 1999.

[12] G. Gendt, G. Dick, C. Reigber, M. Tomassini, and Y. Liu, "Demonstration of NRT GPS Water Vapor Monitoring for Numerical Weather Prediction in Germany," in *International Workshop on GPS Meteorology*. Tsukaba, Japan, 2003.

[13] A. S. Jensen, C. Marquardt, H.-H. Benzon, M. S. Lohmann, and A. S. Nielsen, "Evaluation of the Processing of Radio Occultation Signals by Reconstruction of the Real Signals," in *Atmosphere and Climate - Studies by Occultation Methods*, U. Foelsche, G. Kirchengast, and A. Steiner, Eds. Berlin Heidelberg, New York.: Springer, 2006, pp. 113-125.

[14] M. E. Gorbunov, K. B. Lauritsen, A. Rhodin, M. Tomassini, and L. Kornblueh, "Radio Holographic Filtering, Error Estimation, and Quality Control of Radio Occultation Data," *Journal of Geophysical Research*, vol. 111, 2006.

[15] R. A. Anthes, C. Rocken, and Y. H. Kuo, "Applications of COSMIC to Meteorology and Climate," *Terrestrial, Atmospheric and Oceanic Sciences*, vol. 11, pp. 115-156, 2000.

[16] F. R. Kursinski, G. A. Hajj, J. T. Schofield, R. P. Linfield, and K. R. Hardy, "Observing the Earth's Atmosphere with Radio Occultation Measurements using the Global Positioning System," *Journal of Geophysical Research*, vol. 102, pp. 23429-23465, 1997.

[17] C. Reigber, "GPS Atmosphere Sounding-An Innovative Approach for the Recovery of Atmospheric Parameters," in *HGF Strategy Fund Proposal*. Potsdam, Germany, 1998.

[18] J. Wickert, R. Galas, G. Beyerle, R. Konig, and C. Reigber, "GPS Ground Station Data for CHAMP Radio Occultation Measurements," *Physical Chemical Earth*, vol. 26, pp. 503-511, 2001.

[19] C. Dunn, J. Kim, Y. Bar-Sever, S. Desai, B. Haines, D. Kuang, G. Franklin, I. Harris, G. Kruizinga, T. Meehan, S. Nandi, D. Nguyen, T. Rogstad, J. B. Thomas, J. Tien, L. Romans, M. Watkins, S.-C. Wu, S. Bettadpur, and W. Bertiger, "GPS Augments Gravity Measurements," in *GPS World*, 2003.